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S. Mario De Corso
Engineer
Westinghouse Research Laboratories
East Pittsburgh, Pennsylvania

and

Roland L. Coit, Assoc.Member ASME
Development Engineer
Westinghouse Electric Corporation
Lester, Pennsylvania

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MEASUREMENT OF TOTAL EMISSIVITIES OF GAS TURBINE COMBUSTOR MATERIALS

By S. M. DeCorso and R. L. Coit

ABSTRACT

A method of measuring total emissivity is presented with a description of the apparatus used. Data are presented showing the emissivity of several metals and ceramic coatings as functions of temperature, surface treatment and previous history of the material.

NOMENCLATURE

The following nomenclature is used in the paper:

e_t = total emissivity

e_λ = spectral emissivity

F = constant arising from the thermopile calibration; equal to

$$\frac{\Delta mv_b}{\left(\frac{T}{1000}\right)^4}$$

F_1 = dimensionless factor defining geometry of a particular thermopile, as it concerns radiant heat transfer

Δmv = thermopile emf in mv, corrected for the "zero" reading when viewing a hot body

Δmv_b = thermopile emf in mv, corrected for "zero" reading when viewing a black-body

Δmv_s = thermopile emf in mv, corrected for "zero" reading when viewing a nonblack source

T = temperature of a body, deg R

T_a = ambient temperature, deg R

T_R = radiation temperature of a body at true temperature, T, deg R

W_b = radiant flux density from a black-body, Btu/ft^{2}sec

W_s = radiant flux density from a non-black source, Btu/ft^{2}sec

σ = Stefan-Boltzmann constant, Btu/ft^{2}hr deg R^4

ρ = reflectance of a hot body for radiation at its own temperature

Special
A-1

ρ' = reflectance of a hot body at some temperature for radiation at a different temperature

INTRODUCTION

This paper presents a means of measuring the total emissivities of various gas turbine combustor materials and gives data obtained for some of these materials. A more thorough knowledge of this field will permit selective use and treatment of materials to take full advantage of emissive properties to reduce combustor wall temperatures. The overheating of combustor walls causing "hot-spots" is one of the primary causes of combustor failure.

It is evident that the emissivities of both the inner surface (flame side) and outer surface of a combustor wall have an effect on the temperature of the wall. Combustion tests made by one of the authors (1)[1] showed that the radiant heat transfer from the flame is quite important. These tests showed that a change from diesel fuel oil to residual fuel oil caused combustor wall temperature increases ranging from 250 F to 500 deg F.

To evaluate different flame-tube materials and coatings it is convenient to measure their thermal emissivities under controlled conditions which are independent of those existing during actual operation or combustion testing. The temperature range chosen for these measurements was 800 F to 2100 F.

The device selected for determining total emissivities consists of a thermopile which views a radiating source through an aperture of fixed dimensions. The thermopile receives radiation alternately from a black-body source and from the test specimen, both at the same temperature. A comparison of the respective thermoelectric emf provides a value of the total emissivity. The general method and procedure followed is similar to that of Sully, et al (2).

THEORETICAL BASIS OF METHOD

The total emissivity, e_t, is defined as the ratio of the total radiant flux from a source to that from a black-body at the same temperature; i.e.

$$e_t = \frac{W_s}{W_b} = \frac{e_t T^4}{T^4}$$

The general arrangement of the thermopile, black-body source, and specimen is shown in Fig. 1. The thermopile emf, measured by means of a potentiometer, will be some function of the temperature difference between the hot and cold junctions of the thermopile, This temperature difference in turn is a function of the net radiant energy falling on the receiver element (which contains the hot junctions). Let T be the temperature of the source, and T_a the ambient temperature, both in degrees R, then the net radiant heat transfer to the receiver when it views a black-body source is $F_1 \sigma (T^4 - T_a^4)$, since the receiving element has a coating which can be considered black. This follows from the

[1] Underlined numbers in parentheses refer to the Bibliograph at the end of the paper.

Stefan-Boltzmann law. F_1 is a geometry factor which is characteristic of the particular thermopile and aperture dimensions. As concerns the thermopile, the ambient temperature refers to the temperature of its surroundings; i.e., the thermopile housing and shutter.

The net radiant heat transfer to the receiving element when it views a nonblack-body is (3)

$$F_1\sigma\left[e_t T^4 + \rho' T_a^4 - T_a^4\right]$$

The term $\rho' T_a^4$ represents radiation which originates from the surroundings at T_a and is reflected from the hot body to the receiving element. ρ' is the reflectance of the hot body for radiation from the ambient surroundings, and in general differs from ρ, which is the reflectance of the hot body for radiation at its own temperature. If the hot body is assumed to be a "gray body" then ρ' is equal to ρ. The ratio of emf obtained from the thermopile viewing a nonblack-and a black-body source is then

$$\frac{\Delta mv_s}{\Delta mv_b} = \frac{f\left[F_1\sigma\left(e_t T^4 + \rho' T_a^4 - T_a^4\right)\right]}{f\left[F_1\sigma\left(T^4 - T_a^4\right)\right]} \quad \ldots\ldots (1)$$

For the energy quantities being measured here $T^4 \gg T_a^4$ so that ρ' may be taken as equal to ρ without serious error. For a solid radiator

$$\rho = (1 - e_t)$$

and

$$\frac{\Delta mv_s}{\Delta mv_b} = f_1\left[\frac{F_1\sigma e_t\left(T^4 - T_a^4\right)}{F_1\sigma\left(T^4 - T_a^4\right)}\right] \quad \ldots\ldots (2)$$

which reduces to

$$\frac{\Delta mv_s}{\Delta mv_b} = f_1\ (e_t) \quad \ldots\ldots\ldots\ldots (3)$$

From Fig. 2, the calibration curve of the thermopile

$$\Delta mv_b = F\left(\frac{T}{1000}\right)^4 \quad \text{where } F = \text{const} \quad \ldots\ldots (4)$$

and since by definition

$$T_R^4 = e_t T^4$$

$$\Delta mv_s = F\left(\frac{T_R}{1000}\right)^4 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

hence from Equations (4) and (5)

$$\frac{\Delta mv_s}{\Delta mv_b} = e_t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Thus comparing Equations (3) and (6), for this apparatus

$$f(e_t) = e_t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

It should be noted that this latter relation is valid only when

$$F = \frac{\Delta mv_b}{\left(\frac{T}{1000}\right)^4} = \text{const}$$

If F is not constant, suitable corrections would have to be made at each value of T in accordance with the function, $f(e_t)$. Burgess and Foote (4) indicate that in general for any given thermopile arrangement, F will not be constant when the temperature of the source is varied.

The value of e_t obtained in our tests is the normal emissivity of the test specimen.

If one considers absorption of radiant energy by the gas intervening between the radiating source and the thermopile, only the water vapor present in the air need be considered (5). This correction would vary with the humidity, but since it cannot exceed about 1 per cent it has been neglected.

DESCRIPTION OF APPARATUS

Thermopile. The thermopile consists of eight thermojunctions of 3-mil-diam constantan and chromel wire, with the hot junctions fastened in good thermal contact between two thin platinum disks of 1/16 in. diam. The face of one of the disks is blackened with a mixture of varnish and lampblack to form a black-body reveiver. The cold junctions are located away from the hot junctions and are well shielded from incoming radiation. A Leeds and Northrup double-range portable millivolt indicator type 8662 was used to measure the emf generated by the thermopile.

Fastened to the open end of the thermopile housing was a water-cooled shield which contained a centrally located circular aperture of fixed size (0.25 in. diam for these tests.) This aperture was always held in a fixed position relative to the thermopile receiving element, thereby determining the solid angle from which radiation reached the receiver. Sliding in flanges on this shield, a water-cooled shutter could be moved so as to cover the aforementioned aperture. Water from a constant-temperature bath was circulated continuously through the shield and shutter to insure that radiation from these parts was always at a constant intensity. When the thermopile was set to view the test strip instead of the black-body, an additional water-cooled shield was interposed between the test strip and the primary shield to reduce the cooling load on the latter. The face of this additional shield which confronts the test specimen was blackened with soot to avoid repeated reflections between the test strip and the shield. If the face were not blackened, the emissivity obtained would not be that of the strip alone but that of the strip-shield configuration.

Black-Body Source. The heating coil of the black-body consisted of a spiral of Kanthal wire enclosed by insulation. The furnace is shown in Fig. 1. The Kanthal wire coil is supported by a ceramic cylinder which is insulated by magnesia held in a metal jacket. Pipe insulation was used outside the metal jacket at the ends in order to reduce the heat loss at the ends of the furnace. The inner walls of the furnace form a cylinder 3 in. diam and 21 in. long, with 3/4 in. viewing hold at one end. A target disk was located as shown in Fig. 1, at a distance of 13 in. from the viewing end of the furnace. The disk was made of stainless steel and the face was serrated with vee-shaped grooves having an included angle of 45 deg to increase the emissivity of the face of the disk. Since the disk was the principal source of radiation from the furnace cavity to the thermopile, it was important that its emissivity be a close approximation to that of a black-body and that its temperature be uniform and accurately measured. Hence five 0.012-in-diam chromel-alumel thermocouples were peened into the target disk in order to determine the temperature. After oxidation at 2100 F the emissivity of the target disk can be taken as greater than 0.98 so that radiation from other surfaces inside the furnace is of secondary importance (6).

Test-Strip Arrangement. The test specimen was heated by passing an electrical current through it using a constant-voltage supply with a maximum power of 7000w at 700a. The arrangement of the specimen holder is shown in Fig. 1. The area viewed by the thermopile lies within a circle of 1/2 in. diam at the center of the specimen. This area was kept at a minimum to reduce possibility of large temperature gradients across it. The specimen strips are 1-1/2 in. wide x 5 in. long and approximately 0.040 in. thick with the ends clamped in electrodes.

Three thermocouples of 0.005 in. diam chromel-alumel wire were peened into the specimen from the side opposite the thermopile and lying within the circle which encloses the viewed area. The conduction error of the thermocouples was found to be negligible. This conduction error was determined by comparing the temperature readings of two thermocouples peened into the strip at a point from opposite sides. The leads on one of the thermocouples was led out normal to the surface while on the other they were kept close to the surface of the heated strip.

Since the thermocouple beads ranged from 20-30 mils and the specimen thickness ranges from 30 to 50 mils the temperature at the bead can be taken as the temperature at the face of the specimen. When a ceramic coating was used a correction was made based on the thickness of the coating, its thermal conductivity, and the temperature of the metal strip.

The thermal conductivity of the ceramic coating was obtained in the following manner: With the test specimen heated to some arbitrary temperature a temperature reading of the coating surface was obtained using an optical pyrometer operating at 0.665 μ. A pyrometer reading also was obtained for the black or uncoated side of the specimen. Since the emissivity of the uncoated metal was known and that of the ceramic coating could be calculated approximately from the data, a correction of the readings could be made to obtain the temperature of the coated and uncoated surfaces. The difference of these was taken as the temperature drop through the coating. The heat-transfer coefficient at the surface of the ceramic coating was calculated and the thickness of the coating was known; then equating the heat flow at the surface of the coating to the heat flow by conduction through the coating yields a value of thermal conductivity.

The two sizes of chromel-alumel thermocouples used (0.005 and 0.012 in.) were calibrated against a standard platinum-platinum 10 per cent rhodium thermocouple obtained from the National Bureau of Standards. The curve obtained is shown in Fig. 3. In this figure the sequence in which the readings were taken is indicated by the numbers next to the points. Note that upon initial heating there is only a slight correction, but at temperatures above 1800 F the correction required becomes larger. Once the thermocouples have been heated above 1800 F, the corrections required at all temperatures are larger than the initial corrections. The corrections shown in Fig. 3 were applied to all temperatures measured with chromel-alumel couples to obtain corrected temperatures. If this temperature correction is ignored a maximum error in emissivity of 1.5 per cent would result.

TEST PROCEDURE

With the thermopile in position opposite the hot radiating source the procedure followed in obtaining emf readings was to obtain successive emf readings with the shutter closed, open, and closed again. The average of the first and third readings was considered to be a zero reading. The difference of the second reading and the zero reading was Δmv, the emf due to radiation from the source.

It was found that instead of viewing alternately the black-body source and the test strip, the most convenient procedure was to view the black-body over the full range of temperatures, after which the apparatus would be considered calibrated. The testing of specimens could then proceed with only an occasional return to the black-body for a check of the original calibration.

The results of this calibration with the furnace as the black-body source are shown in Fig. 2 where the ordinate is

$$F = \frac{\Delta mv_b}{\left(\frac{T}{1000}\right)^4}$$

and the abscissa is the black-body temperature in degrees F.

The emf readings with the thermopile opposite the test strip were obtained in the same manner as just indicated, with the ratio of $\Delta mv_s/\Delta mv_b$ being the emissivity of the test strip.

To obtain spectral band emissivities four filters were used. These filters were CaF_2, LiF, fused quartz and pyrex glass. From tests with the black-body the cut-off wave lengths of these filters were found to be 8.9, 5.8, 3.7, 2.55 μ, respectively.

DISCUSSION OF EXPERIMENTAL RESULTS

Heat-Resistant Alloys. In order to determine the effect of time and temperature upon emissivity, as-rolled specimens of Inconel, Nichrome V and type 310 stainless steel were tested over the range from 800 - 1500 F, then heated at 1500 F for additional time increments. After each period at 1500 F the emissivity as a function of temperature was measured. After completing the tests at 1500 F, the same specimen was heated at 1800 and 2100 F and the effect of time at these temperatures was evaluated. Results of these tests are shown in Figs. 4 and 5. Fig. 4(a) and 5(a) present the emissivity versus temperature after oxidation at 1500, 1800 and 2000 F or 2100 F for various lengths of time. The effect upon emissivity at 1400 F of prolonged heating at 1500, 1800 and 1500, 1800, 2000 F is shown in Figs. 4(b) and 5(b) for Inconel and Nichrome. For the Nichrome specimen the emissivity increases only slightly after the first 40 min. For the Inconel specimen the increase in emissivity is slight after the first 15 min.

The emissivity of Nichrome V, Inconel, and Type 310 stainless steel was measured as a function of temperature, surface condition and previous oxidation. The sequence used in obtaining the test points was as follows:

1 Obtain readings from 900 to 1500 F.

2 Oxidize at 1500 F for 15 min.

3 Obtain readings from 900 to 1500 - 1800 F.

4 Oxidize at 1800 F for 15 min.

5 Obtain readings from 900 to 1800 - 2100 F.

6 Oxidize at 2100 F.

7 Obtain readings from 900 to 2100 F.

This procedure was used to obtain the data plotted in Figs. 6, 7 and 8. These figures provide a comparison of Nichrome V, Inconel and type 310 stainless steel in the as-rolled and sandblasted condition. Each of the curves except the below 1500 F curves show a nearly linear increase of emissivity with temperature with the slope of the curves decreasing as the oxidation temperature is increased. In the as-rolled condition for corresponding conditions Inconel had the highest emissivity with type 310 stainless next and Nichrome V having the lowest emissivity. This effect was more pronounced the lower the temperature. In the sandblasted condition no such relationship is evident. It is evident that sandblasting increases the emissivity of the materials, there being a larger increase at the lower temperatures.

This increase due to sandblasting is greatest in the case of Nichrome with type 310 and Inconel next in order.

DISCUSSION OF RESULTS

Table 1 gives values of emissivity increase as a result sandblasting are obtained at 1300 F for Nichrome, Inconel, and type 310 stainless steel.

Table 1 Value of Emissivity Increase as a Result of Sandblasting

	Oxidation temp, deg F	Total Emissivity, e_t		Emissivity increase, Δe_t
		As-Rolled	Sandblasted	
Nichrome	1500	0.36	0.81	0.45
	1800	0.60	0.83	0.23
	2100	0.80	0.87	0.07
Inconel	1500	0.69	0.75	0.06
	1800	0.76	0.90	0.14
	2100	0.88	0.91	0.03
Type 310	1500	0.56	0.82	0.26
	1800	0.67	0.91	0.24
	2100	0.89	0.93	0.04

Thus for applications of Nichrome and type 310 at oxidation temperatures below 1800 F a considerable increase in emissivity can be obtained by sandblasting. The behavior of Inconel appears to be unusual in that the increase due to sandblasting was not as large as for the other two specimens. It is interesting to note that well-oxidized Type 310 sandblasted at 2100 F closely approaches a black-body radiator.

Mild-Steel Specimen. In Fig. 9 emissivity data for mild steel (SAE 1020), as-rolled, is plotted for the temperature range 800 to 1500 F. The emissivity on the initial run increases from 0.83 at 800 F to a peak of 0.97 at 1140 F and falls off to 0.92 at 1500 F. A second run on the

same specimen showed that oxidation at 1500 F had lowered the emissivity slightly over the whole range.

Radiation Suppressive Coatings. Several types of ceramic coatings were evaluated with the object of obtaining a suitable coating of low emissivity. The coatings were obtained from several sources which included the Solar Aircraft Company; University of Illinois, Department of Ceramic Engineering; and the Fulmer Research Institute, England. The two latter groups have published descriptions of their coatings (7), (8).

A commonly used coating, National Bureau of Standards A-418, which was developed primarily to withstand corrosive effects was tested and the emissivity data are shown by the curves in Fig. 10. While its emissivity decreases with increasing temperature, it did not go below 0.86 in our tests.

Fig. 11 (coating 5210-TA1K) presents the emissivity of another type of coating tested. The change in emissivity after heating is probably caused by the fusion of some elements in the coating. This type and the A-418 do not have emissivities low enough to be considered in a radiation suppression application.

The emissivity of a third type of coating is shown in Fig. 12. The emissivity of this coating reaches a value of 0.58 at 1600 F. Upon further heating the emissivity increases, indicating that fusion of the coating is occurring. Heating to 2030 F in this case destroyed the low emissivity properties of the coating, as is shown by the upper curve of Fig. 12.

Fig. 13 presents the emissivities of a fourth group of coatings. The lowest total emissivity attained by this group is 0.42 for coating 216 at a temperature of 1800 F. The characteristics of coating 216 were not changed appreciably by heating the specimen to 2000 F as is shown by curve D, Fig. 13.

Comparision of Spectral Emissivities of Inconel Sheet and Ceramic Coating A417/235. The variation of spectral emissivity with wave length for Inconel sheet and coating A417/235 is shown in Fig. 14. The emissivities used here were obtained for a band of wave lengths using the four filters described previously. In Fig. 14 each band emissivity is plotted at a wave length which equally divides the black-body energy in that band.

The data for Inconel were obtained at two temperatures, 1400 and 1500 F, while the data for the ceramic coating were obtained at several temperatures ranging from 800 to 1800 F. The spectral emissivity should not vary with temperature where a particular surface condition is maintained. This is seen to be true for the coating A417/235, and constitutes a check on the method and apparatus used.

In going from 2μ to 12μ the spectral emissivity of Inconel decreases from 0.8 to 0.21 while that of coating A417/235 increases from 0.3 to 1.0. Neither material can be considered "gray" over this range of wave lengths.

If the spectral distribution of the radiation from the flame is known, spectral-emissivity data such as that shown in Fig. 14 can be used to calculate the effectiveness of a radiation-suppressive coating by taking $\epsilon_\lambda = a$, for the wall. For example consider the case of a combustor wall and a flame as two large parallel surfaces, with the flame taken as a black-body at 3500 F. The ratio of the net radiant heat transfer to the combustor wall for an Inconel wall to that for the ceramic (A417/235) wall ranges from 2.1 to 2.8 for wall temperatures of 1000 F and 1500 F, respectively.

RESULTS AND CONCLUSIONS

A procedure and apparatus for measuring emissivities of strip material and ceramic coatings are presented. The method utilizes a thermopile which views the test specimen through an aperture in a controlled-temperature shield. The apparatus is calibrated periodically by means of a black-body, which is described. The calibration of the thermopile arrangement showed that the ratio of the thermopile emf to the fourth power of the absolute temperature of the black-body is a constant over the temperature range 800 to 2000 F. This enables one to take as the emissivity of a source simply the ratio of the thermopile emf when viewing the source, to the black-body emf at the corresponding temperature.

Emissivity data are presented for sheet material in the as-rolled and sandblasted condition, for type 310 stainless steel, Inconel, Nichrome, and mild steel. In addition data were obtained for several types of ceramic coatings on the same metals. Values of spectral emissivity versus wave length are shown for Inconel sheet as-rolled and a typical radiation-suppressing coating. The spectral emissivity increases with decreasing wave length for the Inconel while the opposite is true for the ceramic coating A417/235.

The data presented show that combustor wall temperatures can be reduced by sandblasting of the external surfaces and application of a suitable ceramic coating on the internal surfaces. If a black-body flame at 3500 F is assumed inside the combustor, ceramic coating of the inside of an Inconel combustor will reduce the radiant heat transfer to the combustor wall by nearly one-third.

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Captions for Illustrations

Fig. 1 Arrangement of furnace, specimen and thermopile

Fig. 2 Parameter F versus temperature in deg F

Fig. 3 Calibration curves for Chr-Al thermocouples

Fig. 4(a) Effect of previous heating upon emissivity of Inconel sheet

Fig. 4(b) Effect of time and temperature upon emissivity of Inconel sheet at 1400 deg F

Fig. 5(a) Effect of previous heating upon emissivity of Nichrome V sheet

Fig. 5(b) Effect of time and temperature upon the emissivity of Nichrome V sheet at 1400 deg F

Fig. 6(a) Total emissivity versus temperature, Nichrome V as-rolled

Fig. 6(b) Total emissivity versus temperature, sandblasted Nichrome V

Fig. 7(a) Total emissivity versus temperature for Inconel, as-rolled

Fig. 7(b) Total emissivity versus temperature, sandblasted Inconel

Fig. 8(a) Total emissivity versus temperature, type 310 stainless steel as-rolled

Fig. 8(b) Total emissivity versus temperature, sandblasted type 310 stainless steel

Fig. 9 Total emissivity versus temperature, mild steel, as-rolled

Fig. 10 Total emissivity versus temperature, Nichrome V coated with 2 mils of A-418 ceramic

Fig. 11 Total emissivity versus temperature, ceramic coating 5210-TA1K

Fig. 12 Total emissivity versus temperature, ceramic coating 117-23

Fig. 13 Total emissivity versus temperature, ceramic coatings A417/234; A417/235; 216

Fig. 14 Spectral emissivity versus wave length for Inconel and coating A417/235

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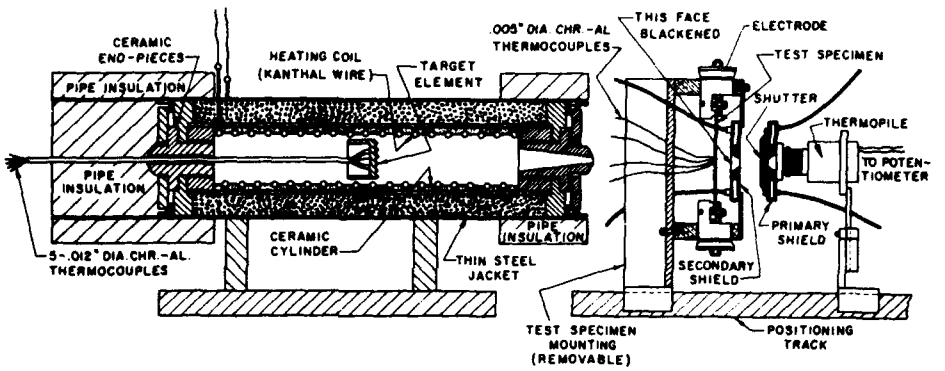
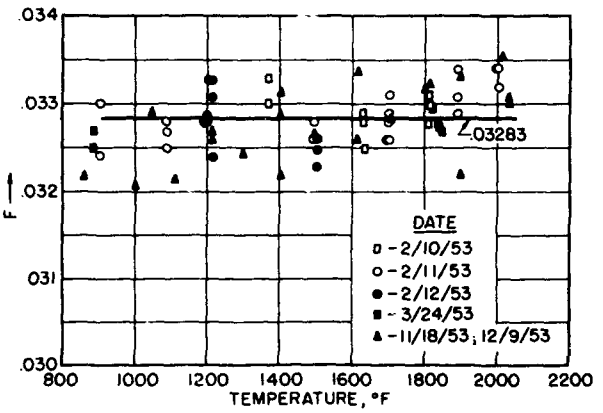


ARRANGEMENT OF FURNACE, SPECIMEN AND THERMOPILE.

POSITION SHOWN: VIEWING TEST SPECIMEN
TO VIEW FURNACE: REMOVE SPECIMEN MOUNTING
AND SLIDE THERMOPILE INTO POSITION OPPOSITE FURNACE.

Fig.1



PARAMETER "F" VS. TEMPERATURE IN °F

$$\left(\text{WHERE } F = \frac{\Delta mv_b}{\left(\frac{T}{1000}\right)^4}\right)$$

Fig.2

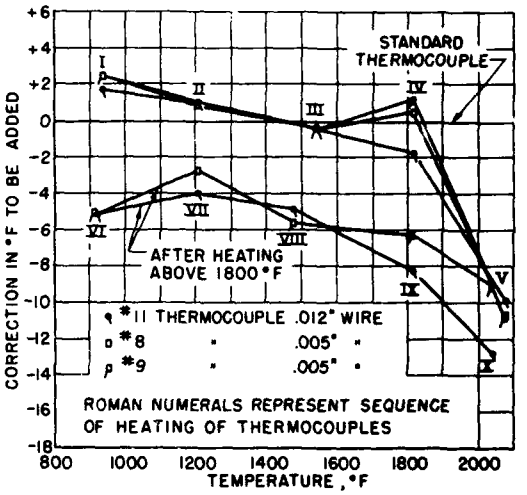


Fig.3

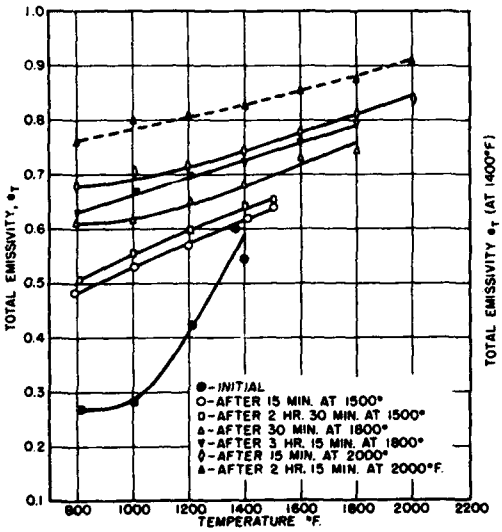


Fig.4(a) (right)

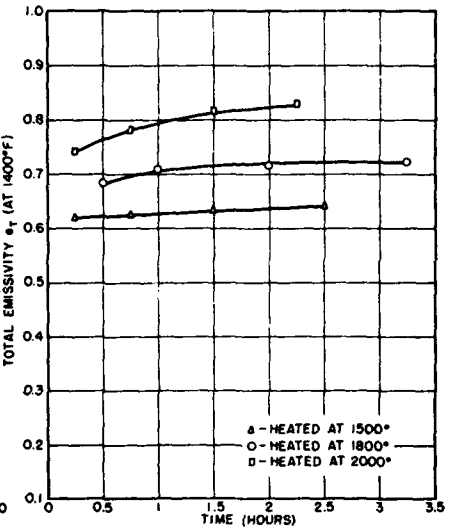


Fig.4(b) (left)

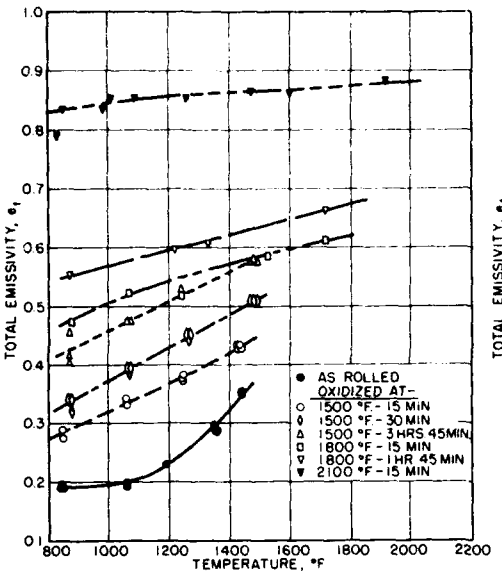
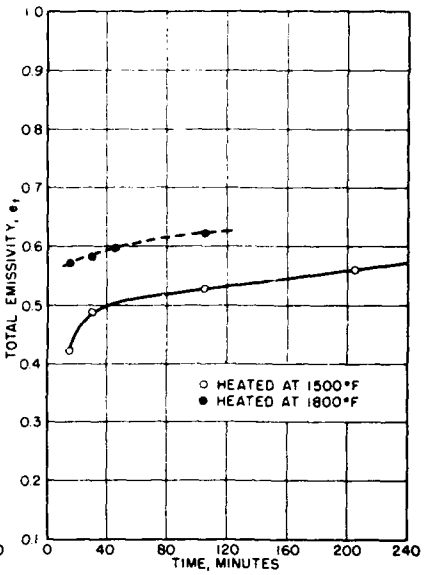
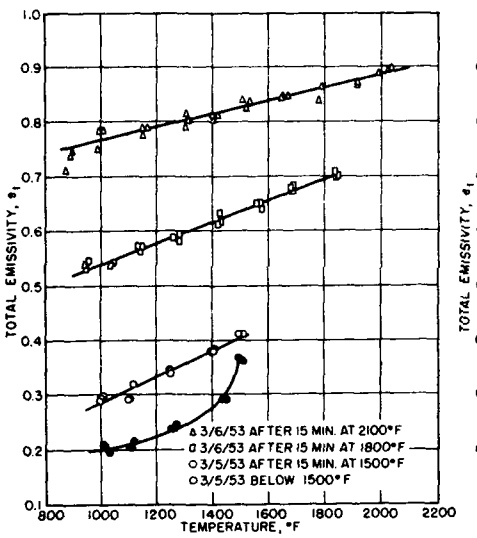


Fig.5(a) (right)



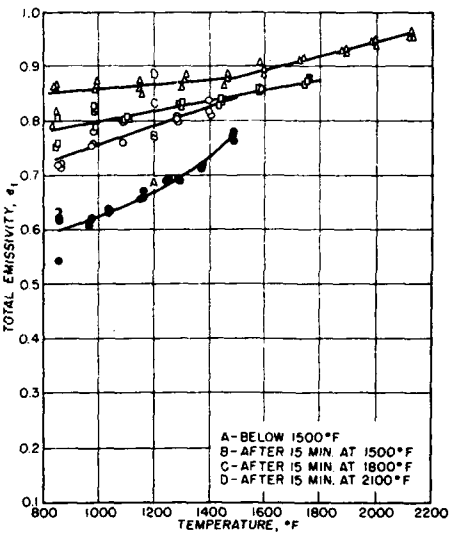
Nichrome V

Fig.5(b) (left)



Nichrome V as rolled

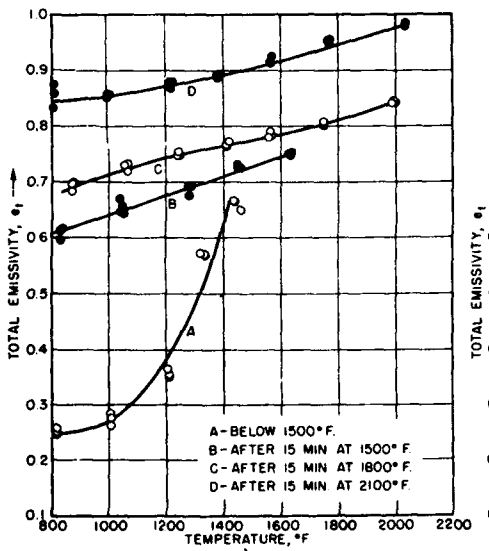
Fig.6(a) (right)



Nichrome V sand blasted

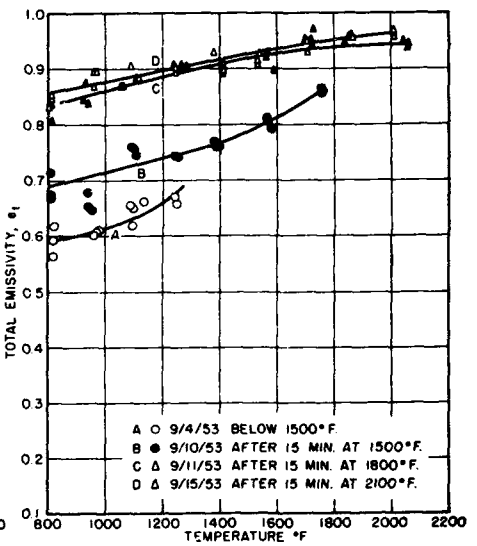
Fig.6(b) (left)

Inconel



as rolled

Fig.7(a) (right)



sand blasted

Fig.7(b) (left)

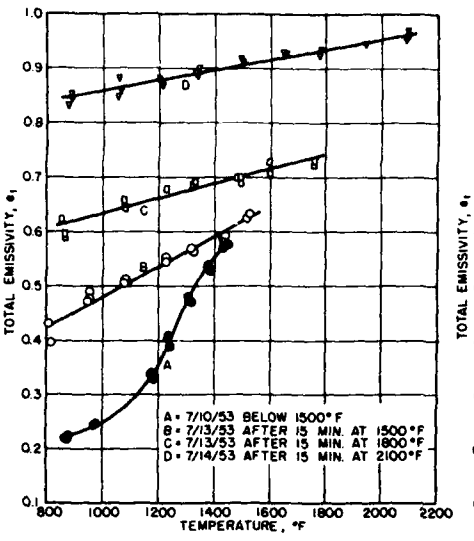


Fig.8(a)

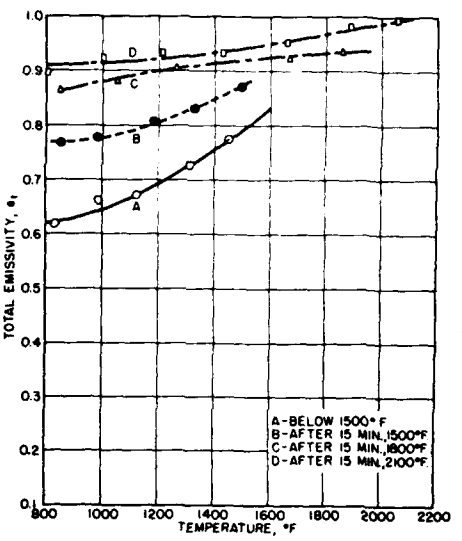


Fig.8(b)

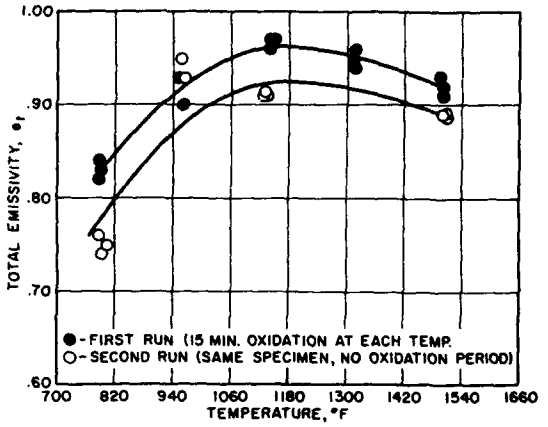


Fig.9

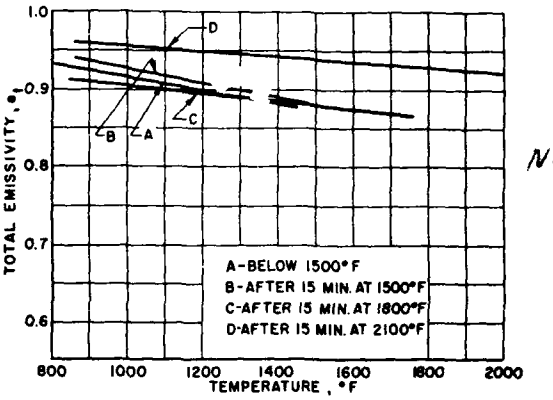


Fig.10

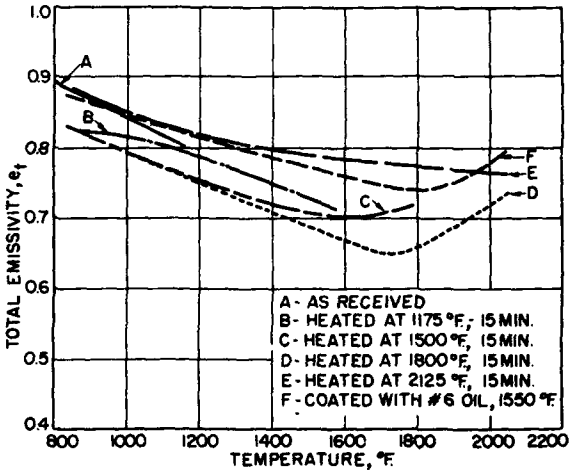


Fig.11

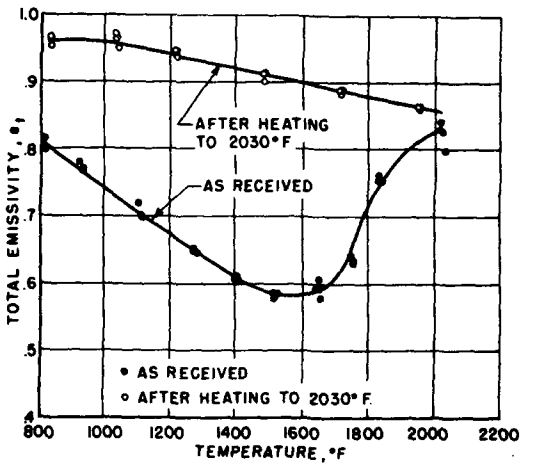


Fig.12

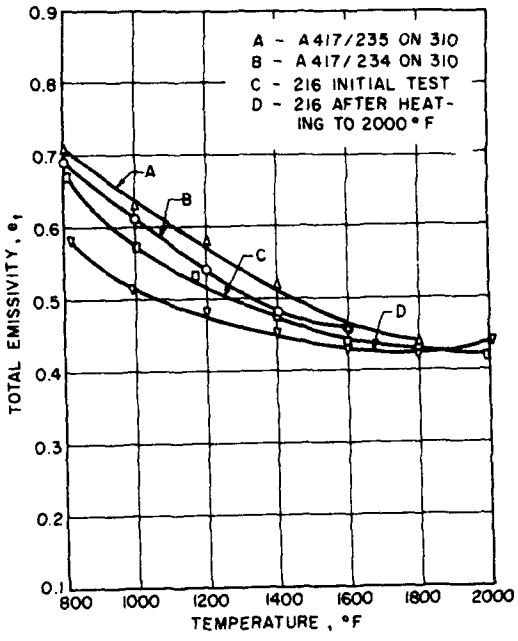

A - A417/235 ON 310
B - A417/234 ON 310
C - 216 INITIAL TEST
D - 216 AFTER HEATING TO 2000°F
A
B
C
D
TOTAL EMISSIVITY, ϵ_t
TEMPERATURE, °F
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
800
1000
1200
1400
1600
1800
2000

Fig.13

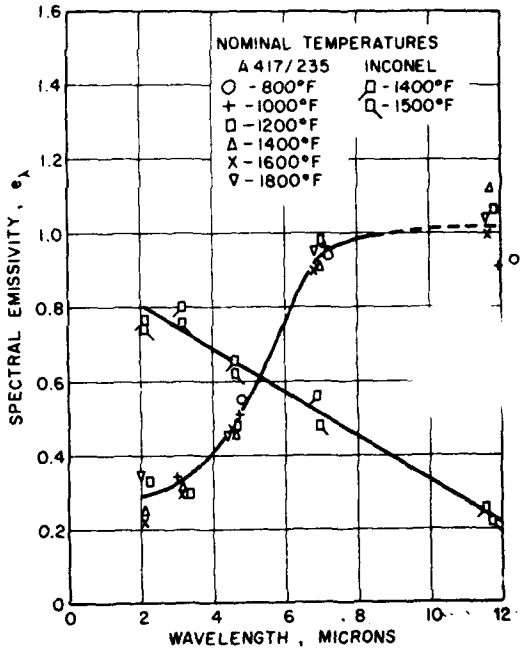

NOMINAL TEMPERATURES
A 417/235
INCONEL
○ - 800°F
+ - 1000°F
□ - 1200°F
Δ - 1400°F
X - 1600°F
▽ - 1800°F
□ - 1400°F
□ - 1500°F
SPECTRAL EMISSIVITY, ϵ_λ
WAVELENGTH, MICRONS
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
2
4
6
8
10
12

Fig.14